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**Citation for published version:**

Erden, MS & Billard, A 2015, 'Robotic Assistance by Impedance Compensation for Hand Movements While Manual Welding', *IEEE Transactions on Cybernetics*, vol. 46, no. 11, pp. 2459-2472.  
<https://doi.org/10.1109/TCYB.2015.2478656>

**Digital Object Identifier (DOI):**

[10.1109/TCYB.2015.2478656](https://doi.org/10.1109/TCYB.2015.2478656)

**Link:**

[Link to publication record in Heriot-Watt Research Portal](#)

**Document Version:**

Peer reviewed version

**Published In:**

IEEE Transactions on Cybernetics

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# Robotic Assistance by Impedance Compensation for Hand Movements while Manual Welding\*

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**Abstract—** In this paper we present a robotic assistance scheme which allows for impedance compensation with stiffness, damping, and mass parameters for hand manipulation tasks and we apply it to manual welding. The impedance compensation does not assume a preprogrammed hand trajectory. Rather, the intention of the human for the hand movement is estimated in real time using a smooth Kalman filter. The movement is restricted by compensatory virtual impedance in the directions perpendicular to the estimated direction of movement. With airbrush painting experiments we test three sets of values for the impedance parameters as inspired from impedance measurements with manual welding. We apply the best of the tested sets for assistance in manual welding and perform welding experiments with professional and novice welders. We contrast three conditions: welding with the robot's assistance, with the robot when the robot is passive, and welding without the robot. We demonstrate the effectiveness of the assistance through quantitative measures of both task performance and perceived user's satisfaction. The performance of both the novice and professional welders improves significantly with robotic assistance compared to welding with a passive robot. The assessment of user satisfaction shows that all novice and most professional welders appreciate the robotic assistance as it suppresses the tremors in the directions perpendicular to the movement for welding.

## I. INTRODUCTION

IN this study we develop a robotic assistance scheme that allows to compensate hand impedance in terms of three impedance parameters – stiffness, damping, and mass – and we apply it to an industrial task, manual welding. The scheme of robotic assistance by impedance compensation was inspired by our hand impedance measurements across professional and novice welders [1, 2]. These measurements showed that novice welders demonstrate less hand impedance than the professional welders, with a significant difference in the direction perpendicular to the welding line on the metal plate. This observation motivated us for the present study to compensate the impedance of the novice welders by introducing virtual impedance in the directions

perpendicular to the intended movement of the hand with an interactive robot. We estimate the intended direction of movement for welding using a smooth Kalman filter in real time.

Automated welding robots are widely used in industry [3]. However, automation is not always possible due to the complexity and variety of welding tasks [4, 5]. Therefore, manual welding is an indispensable process in many branches of industry [6]. Manual welding requires highly refined professional skills. A formal course for any single type manual welding lasts two to four weeks; around 85% of the time is devoted to welding practices [7]. Following such training, a welder acquires a professional skill level only after a few years of professional work [8]. Furthermore, whereas skilled welders are getting scarcer and costly [9, 10, 11, 12, 13], the number of different welding processes (arc, laser, friction, etc.) in a factory is increasing [14]. To address these problems, robotic assistance can be used to help novice welders to perform as successful as a professional welder.

In an early approach [15], it was shown that skilled welders were more stable in the motion of the welding torch. In our previous work we determined metrics to classify across skilled and unskilled welding performances based on position variations [16, 17] and developed a robotic assistance by using virtual damping in all directions, irrespective of the intended movement, to suppress hand vibrations [18, 19]. In these works, the interaction forces between the human hand and the torch had not been studied. In a recent study [1, 2] we measured hand impedance during manual welding and identified the differences across novice and professional welders. In the current study we inspire from those hand impedance measurements in order to develop robotic assistance by modifying the virtual impedance of the robot in the directions perpendicular to the intended hand movement.

Impedance learning [20], impedance estimation [21], and variable impedance [22] are used in robot control to regulate contact forces with objects. In [23, 24] impedance control schemes are developed for autonomous control of robots, by inspiration from human impedance studies. An example of human impedance measurement is presented in [25] in conjunction with EMG measurement (see [1] and [38] for others). Variable/adaptive impedance control is applied in physical human-robot interaction for load carrying [26, 27], to assist calligraphy drawing [28], for safe human robot collision [29], for meal assistance considering a potential field in the workspace [30], for gait rehabilitation [31], and for collaborative point-to-point motions [32]. Virtual fixtures

\* This work was supported by European Union under the Marie Curie Intra-European Fellowship of the first author: SkillAssist, PIEFGA-2011-297857.

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[33] are used to provide real time assistance, and incorporated to a scheme where the direction of the force at the end-effector is used to turn on and off the assistive forces [34]. In [35], EMG signals are used to estimate human's hand trajectory and impedance control is applied to an exoskeleton to realize human like motion. In [36], the intentions of a wheelchair user are predicted from joystick inputs for a collaborative robotic assistance. An assistance strategy is developed in [37] for a master-slave teleoperation systems where stiffness is dynamically changed according to the deviation from the desired path and according to the amount of counter forces between the human and the master robot. As opposed to these other works, we incorporate skilled and unskilled hand-impedance measurements in the impedance compensation scheme that we propose for robotic assistance.

We presented an initial form of this assistive scheme, robotic assistance by directional damping [38], where only damping was compensated again by using a smooth Kalman filter as we do in this study, and we applied it when subjects did airbrush painting with their dominant versus non-dominant hands. Different from our previous work, in the current paper we perform the following: (i) We *extend the assistive scheme* to compensate for all three impedance parameters rather than only for damping. We derive sets of values for the impedance parameters from impedance measurements with manual welding [1]. We use these sets with airbrush painting experiments in order to examine the impact of the three parameters and to determine the best set among the tested for assistance. (ii) We *propose and implement an assistive regulator for manual welding* that incorporates the assistive scheme. This regulator makes the system usable for the practical welding process, especially considering stopping, starting of welding, and transfer and placement of the torch in the start and end of the process. (iii) We *apply the overall robotic assistance to the industrial task – manual welding*. (iv) We *assess the usefulness of the assistive scheme with professional and novice welders* in terms of measurable changes in performance during welding with and without assistance. (v) We *further validate the acceptability of the robotic assistance through an assessment of user's perception* of the system's usability and effectiveness in comparison to conventional manual welding without a robot.

Kalman filter, extended Kalman Filter and their modified versions are widely used for trajectory estimation, for example for spacecraft attitude estimation [39], for estimation of position, speed, and orientation of an unmanned air vehicle [40], for state estimation to control the balance of a biped walking robot [41], for position and pose estimation in visual servoing [42, 43] and in robotic catching of flying objects [44]. In [38] and the present study we use a Kalman filter to estimate the intended hand trajectory of the subject from the actual hand position.

Providing robotic assistance by compensating for impedance is close in spirit to the work that attempted to

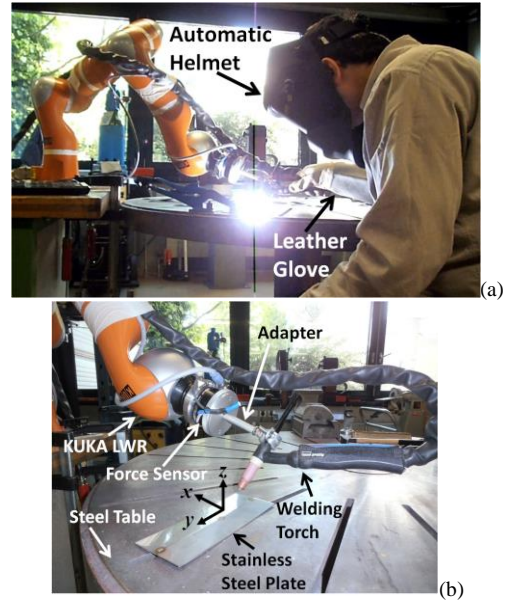


Fig. 1. The experimental setup for interactive manual welding with the KUKA LWR 4+ robot [1].

cancel hand tremor during micro surgery – by using weighted frequency Fourier linear combiner to estimate the magnitude and frequency of hand tremor [45, 46] or by employing reinforcement learning to predict the hand tremor [47] – and to the work that aimed to align a robot's motion with the heart beat during heart surgery – by using an extended Kalman filter with a time-varying Fourier series model for the motion of the heart [48]. In these studies the goal was to estimate the tremor/heart beat and then to move the tool tip in the opposite/same direction via an intermediary actuator for compensation. In our approach, we do not estimate the hand tremor during welding; rather we aim to estimate the intended hand movements. We use the robot not to move the tool tip for movement compensation, but to suppress the tremor at the tool tip before they occur.

In Section II we introduce the robotic setup and the admittance control used for interactive manipulation with the robot. In Section III we review the results of impedance and variance measurements that we presented in the previous study [1] and present the quantitative performance measure applied in this study to assess the robotic assistance. In Section IV we introduce the robotic assistance scheme by impedance compensation. Section V presents the assistive regulator that incorporates the impedance compensation with various other control modalities designed for an easy use of the system in different phases of manipulation before, during, and after actual welding. Section VI presents the results of the quantitative measure of performance of novice and professional welders while welding with the robot, with and without assistance. Section VII presents the results of the questionnaire-based evaluation of the usability and effectiveness of the system by the novice and professional welders in comparison to conventional welding without the robot. Section VIII concludes the paper.

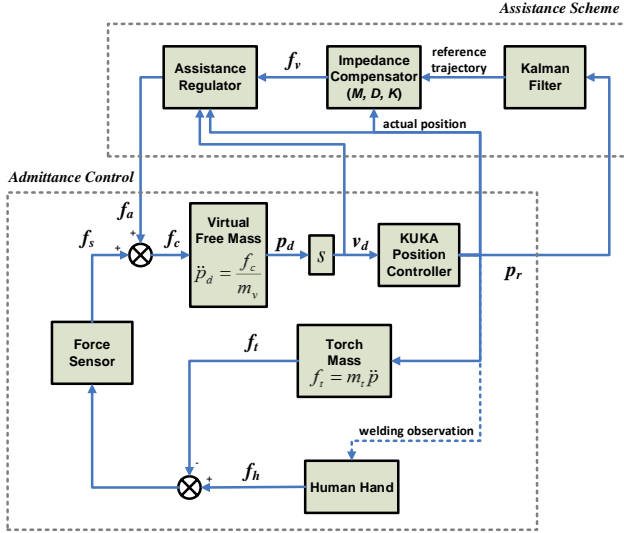


Fig. 2. Block diagram for the admittance control of the KUKA LWR 4+ robot with the assistance scheme.

## II. EXPERIMENTAL SETUP AND SUBJECTS

### A. Apparatus

In this study we use the same interactive manual welding setup as we used in [1], shown in Fig. 1 and composed of the 7 degrees-of-freedom light-weight robot KUKA LWR 4+, an ATI force sensor attached to its end-effector, a standard TIG Welding setup, and a mechanical adapter that attaches the welding torch to the force sensor.

The control of the robot is maintained through a Fast Research Interface (FRI) and a Control Box, both provided by the manufacturing company. In case of no robotic assistance ( $f_a=0$ ), we control the robot in admittance mode by using the force sensor signal ( $f_s$ ) that is sampled at 1 kHz and that corresponds to the difference between the human force applied on the torch ( $f_h$ ) and the inertial force of the torch ( $f_t$ ). We generate a velocity command ( $v_d$ ) and send to the KUKA Position Controller (the Control Box) at a rate of 1 kHz, by emulating a 2 kg virtual mass ( $m_v$ ) at the end effector. The block KUKA Position Controller runs at 3 kHz, which is the servo-control cycle rate provided by the Control Box locally in the joints. Together with the 2 kg virtual mass and 0.4 kg torch, the human feels throughout the manipulation like he/she is manipulating a total mass of 2.4 kg in free space with no gravity.

In the experiments, the subjects welded through the touching edges of two 1.5 mm thick stainless steel plates [Fig. 1(b)] using 40 Amperes DC current and without any external feed. They used leather gloves and a welding helmet, which automatic turns into dark in the presence of electric arc, in order to protect the skin and eyes from the ultraviolet radiation, respectively [Fig. 1(a)]. Since there were no external feed, there were no sparks and molten metal particles spreading around, which made the process easier especially for the novice welders.

### B. Subjects and Experiments

Twelve novice and eight professional welders took part in our experiments. The novice subjects were recruited by e-mail announcement on a voluntary basis among the students of the School of Engineering at EPFL. Their ages ranged between 18-27 ( $21.7 \pm 2.6$ ) years old. The novice subjects did not have any prior experience in welding, except for experiencing it once or twice during their practical courses or in some other occasions. The professional welders were recruited among the technicians working at the mechanical workshops at EPFL. Their ages ranged between 29-63 ( $42.0 \pm 10.6$ ) years old. They had either extensive TIG welding experience or were practicing regularly as a part of their daily job. All the participants were right-handed. The experiment protocol was approved by the Human Research Ethics Committee of EPFL. All participants were provided with an information sheet and they gave their informed consent prior to the experiments.

The subjects performed welding in three conditions: (i) welding with the robot, but the robot was not assisting and acted as a passive device, (ii) welding with the robotic assistance, and (iii) conventional welding without the robot. The novice welders performed the three experiments in random order. The professional welders had performed the experiments (i) around five months earlier with the same setup. They performed the experiments (ii) and (iii) in random order. The data collected from (i) and (ii) are used to quantify the comparison across performances in terms of variance measures. The experience from (ii) and (iii) is used by the subjects to evaluate the effectiveness of the overall robotic system while answering the user questionnaire. Randomization of the order of experiments served to avoid any bias in perception of the robotic assistance by the subjects.

The novice subjects were instructed about the process of welding by one of the authors before the experiments. These instructions included information about the melting conditions and how the melted part should look like for a good weld. The author instructed both novice and professional welders about how to manipulate the torch and demonstrated welding interactively with the robot to each subject. The subjects were told to aim at the best quality welding they can in all three experiments.

The assistance scheme developed here does not assume any preprogrammed welding trajectory. It estimates the direction of welding in real time and provides assistance accordingly. Therefore the metal plates can be placed arbitrarily on the table. In the experiments we placed the metal plates more or less in parallel to the y axis of the robot coordinate frame [Fig. 1(b)] for sake of homogeneity across experiments. Although the edges of the metal plates were straight before welding, during welding, subjects did not follow such straight path due to two reasons. First, as it is usually required and known as the ‘weaving’ action, they went back and forth to the two sides across the contacting edges with millimeter scale deviations in order to achieve a



TABLE I  
MEAN VARIANCE AND IMPEDANCE MEASURES FOR PROFESSIONAL VERSUS NOVICE WELDERS IN X, Y, AND Z DIRECTIONS. STATISTICALLY SIGNIFICANT DIFFERENCES ACROSS PROFESSIONAL AND NOVICE WELDERS ASSESSED WITH ANOVA TESTS ARE INDICATED WITH AN ASTERISK [1]<sup>†</sup>.

	Variance and Impedance Measures, Avg. $\pm$ Std.dev					
	Professional Welders			Novice Welders		
	x	y	z	x	y	z
Variance (over 0.2 Hz) (mm <sup>2</sup> )	0.17 $\pm$ 0.06*	0.48 $\pm$ 0.23	0.61 $\pm$ 0.26*	0.27 $\pm$ 0.12*	0.59 $\pm$ 0.16	0.84 $\pm$ 0.35*
Rate-hardness, rh100 (N/m)	1321 $\pm$ 253*	997 $\pm$ 356	747 $\pm$ 183	1113 $\pm$ 211*	812 $\pm$ 130	662 $\pm$ 168
Mass (kg)	2.9 $\pm$ 0.8	0.6 $\pm$ 0.2	0.8 $\pm$ 0.2	2.6 $\pm$ 0.6	0.7 $\pm$ 0.3	0.9 $\pm$ 0.4
Damping (Ns/m)	44 $\pm$ 13*	19 $\pm$ 5	17 $\pm$ 6	32 $\pm$ 13*	15 $\pm$ 9	12 $\pm$ 8
Stiffness (N/m)	550 $\pm$ 198	432 $\pm$ 238	329 $\pm$ 157	441 $\pm$ 195	344 $\pm$ 68	283 $\pm$ 103

<sup>†</sup>The values in this table slightly and insignificantly differ from that in [1], due to the re-computation of the values with different filtering of signals.



Fig. 3. Deformed metal plate after welding.

balanced melting on both plates. The other reason is that the metals mostly deformed due to the high temperature and bended along the welding line as in Fig. 3. The height of the metal plate from the steel table changed non-homogenously. The welders needed to adapt the height of the torch to this change (in the  $z$  direction) in real time while welding. All these required that the welding line was not preprogrammed and that the assistive scheme adapted to the real time changes in the intentional hand movements.

### III. RECAP OF IMPEDANCE AND VARIANCE MEASUREMENTS

In Table I, we show the previous results of variance and impedance measures across professional and novice welders when they welded interactively with the robot and indicate statistical significance ( $p < 0.05$ ) in difference with an asterisk [1]. The impedance measurements were performed by applying force disturbances and measuring the position deviation of the torch. In this table rate-hardness is a measure of overall impedance [49, 1]; mass, damping, and stiffness are the conventional impedance parameters [1]. We observe that the novice welders have more difficulty in stabilizing the torch along the welding line, with larger variance in the two directions perpendicular to the welding line ( $x$  and  $z$ ). We also observe that the professional welders apply larger impedance (rate-hardness) in these directions compared to the novice welders. The minimum variance occurs in the  $x$  direction with both professional and novice welders, indicating that this is the most important direction for the quality of welding. Among the impedance parameters, damping in the  $x$  direction differs most significantly across professional and novice welders. These results suggest that the novice welders need impedance compensation in the directions perpendicular to the direction of the hand movement while welding.

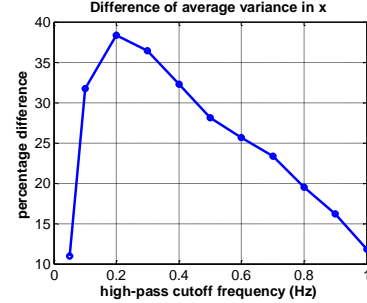


Fig. 4. Percentage difference in the variance of the hand position perpendicular to the welding line on the metal plate (in the  $x$  direction) across professional and novice welders when they welded without assistance. The difference is given with respect to varying cut-off frequency of the high-pass filter applied to the position signal.

#### A. Performance Measure based on Position Variation

In this study we apply similar performance measure as in our previous work [1, 2, 16, 17] to assess the quality difference between welding with and without assistance. We pass the three components of the hand position signal ( $p_x, p_y, p_z$ ) through a high pass filter with a low cutoff frequency (fourth order Butterworth filter) as in (1), in order to eliminate the impact of slow variations, such as due to the intentional back and forth movements across the welding line, intentional changes in the height of the torch tip, and varying speed of welding across experiments. Afterwards we compute the variance of the three components of the position signal as in (2). We also compute the *variation* ( $v$ ) of the magnitude of the position as in (3), by adding the variances in the three directions. For frequency content analysis we construct the filtered position signal,  $r$ , using the filtered components of the position as in (4).

$$p_{fi} = \text{high\_pass\_filter}(p_i, 0.2 \text{ Hz}) \quad (1)$$

$$\left. \begin{aligned} \text{var}(x) &= \text{var}(p_{xf}) \\ \text{var}(y) &= \text{var}(p_{yf}) \\ \text{var}(z) &= \text{var}(p_{zf}) \end{aligned} \right\} \quad (2)$$

$$v = \text{var}(x) + \text{var}(y) + \text{var}(z) \quad (3)$$

$$r = \sqrt{p_{xf}^2 + p_{yf}^2 + p_{zf}^2} \quad (4)$$

In order to determine the cut-off frequency of the high-pass filter we compared the position variance of the hand movement perpendicular to the welding line on the metal plate (in the  $x$  direction) across professional and novice welders when they welded without assistance (Fig. 4). We

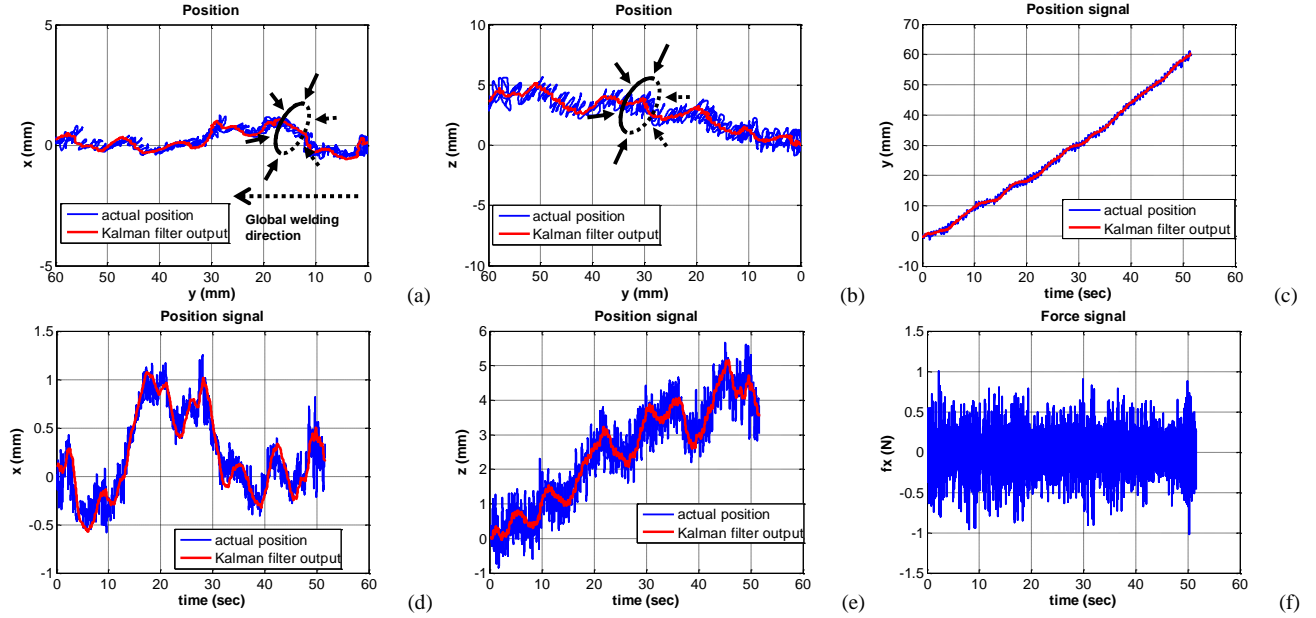


Fig. 5. Position data of a professional welder while welding with the robot without assistance. Position in the (a)  $x$ - $y$  and (b)  $z$ - $y$  planes. Temporal history of (c)  $y$ , (d)  $x$ , (e)  $z$  direction position signals, and (f)  $x$  direction force signal. The Kalman filter output (red smooth lines) is generated in simulation and plotted on top of the welding data (blue scattered lines). The line through the contacting edges of the plates roughly corresponds to the  $x=0$  line. The  $z=0$  level is the starting height for this welding session.

used a high-pass filter with a cut-off frequency in the range  $[0.05, 1.00]$  Hz and plotted the percentage difference of the average values for the two groups with respect to the varying cut-off frequency. We observe that the maximum rate of difference occurs with 0.2 Hz. Therefore we use this value, to access the improvement of the performance with assistance compared to the performance without assistance.

#### IV. ROBOTIC ASSISTANCE WITH IMPEDANCE COMPENSATION

In this section we explain the blocks of Impedance Compensator and Kalman Filter in the assistance scheme in Fig. 2. The impedance compensation is based on applying external impedance in the directions perpendicular to the estimated direction of movement. Fig. 5 shows the spatial and time trajectories of the position data and the time trajectory of the force data perpendicular to the global welding direction, for a sample welding with robot and without assistance by a professional welder.

In Fig. 5(a) we observe that the subject moves the tip of the torch back and forth across the contacting edges of the two plates which roughly corresponds to the  $x=0$  line in this example. We also observe in Fig. 5(b) that the height of the torch increases during welding in order to compensate for the change in the height of the metal due to deformation. We observe the position variations due to the hand tremor along the welding path. The intended path by the subject can be represented with the red line passing in between the actual data points. Our goal is to suppress the hand tremor in the directions perpendicular to this intended line as shown by the arrows.

The direction of intended movement by the subject is not known to the robot; therefore it has to be estimated in real time. Our approach is to estimate that by using a Kalman

filter applied to the actual position signal of the tool. A Kalman filter with an auto-covariance matrix of process disturbance with very low entries can be used in order to construct a hypothetical smooth trajectory from the fluctuating position data. In this way the Kalman filter eliminates in real-time the high frequency fluctuations and generates a smooth path passing almost in the middle of the actual position data, as shown with the red curves in Fig. 5. Here we use a standard Kalman filter with the model of physical dynamics that relate position ( $\mathbf{p}_k$ ), velocity ( $\mathbf{v}_k$ ), and acceleration ( $\mathbf{a}_k$ ) to each other through the sampling time ( $T$ ).

$$\begin{bmatrix} \dot{\mathbf{p}}_k \\ \dot{\mathbf{v}}_k \\ \dot{\mathbf{a}}_k \end{bmatrix} = \begin{bmatrix} 1 & T & T^2/2 \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{p}_k \\ \mathbf{v}_k \\ \mathbf{a}_k \end{bmatrix} \quad (5)$$

The Kalman filter trajectory in Fig. 5 is generated in real-time simulation, meaning that at every instant there is a corresponding reference position. Since this trajectory is rather smooth, we can use it as a reference for the impedance compensation.

Impedance compensation type robotic assistance refers to applying virtual stiffness ( $\mathbf{f}_s$ ), damping ( $\mathbf{f}_d$ ), and mass ( $\mathbf{f}_m$ ) forces in a plane which is perpendicular to the estimated direction of movement intended by the subject. In our overall control scheme, the block Impedance Compensator in Fig. 2 outputs the virtual force ( $\mathbf{f}_v$ ), which is simply the sum of the stiffness, damping and mass related impedance compensation forces in this plane.

$$\mathbf{f}_v = \mathbf{f}_s + \mathbf{f}_d + \mathbf{f}_m \quad (6)$$

In order to find the perpendicular plane to the intended direction of movement we use the velocity vector ( $\mathbf{v}_k$ ) output by the Kalman filter. In the following we explain how each of the stiffness, damping and mass related force is generated.

*Virtual stiffness force:  $\mathbf{f}_s$*

We construct first the vector pointing from the position output of the Kalman filter ( $\mathbf{p}_k$ ) to the actual position ( $\mathbf{p}_a$ ) and then project this vector on the plane perpendicular to the velocity vector output of the Kalman filter ( $\mathbf{v}_k$ ); finally we multiply by the assistive stiffness value ( $S$ ) (7).

$$\mathbf{f}_s = -S \cdot \left( \mathbf{p} - \mathbf{p}_k - \frac{\mathbf{v}_k}{|\mathbf{v}_k|^2} (\mathbf{v}_k \cdot \mathbf{p}) \right) \quad (7)$$

*Virtual damping force:  $\mathbf{f}_d$*

We take the velocity vector commanded to the robot controller ( $\mathbf{v}_d$ ) (Fig. 2), and then project this vector on the plane perpendicular to the velocity vector of the Kalman filter ( $\mathbf{v}_k$ ) and finally multiply by the assistive damping value ( $D$ ) (8).

$$\mathbf{f}_d = -D \left( \mathbf{v}_d - \frac{\mathbf{v}_k}{|\mathbf{v}_k|^2} (\mathbf{v}_k \cdot \mathbf{v}_d) \right) \quad (8)$$

*Virtual mass related force:  $\mathbf{f}_m$*

We take the acceleration output of the Kalman filter ( $\mathbf{a}_k$ ) and then project this vector onto the plane perpendicular to the velocity vector of the Kalman filter ( $\mathbf{v}_k$ ), and finally multiply by the assistive mass value ( $M$ ) (9).

$$\mathbf{f}_m = -M \left( \mathbf{a}_k - \frac{\mathbf{v}_k}{|\mathbf{v}_k|^2} (\mathbf{v}_k \cdot \mathbf{a}_k) \right) \quad (9)$$

In this scheme, all three assistive forces are perpendicular to the velocity vector of the Kalman filter. Therefore, they do not impact the movement along the direction of the velocity vector, but they suppress the variations in the perpendicular directions to this vector. While the virtual damping and stiffness forces act against the deviations of actual trajectory from the Kalman filter trajectory, the mass related force acts against the changes of direction in the Kalman filter trajectory.<sup>1</sup>

The assistive forces do not introduce any force demand along the velocity vector of the Kalman filter, but they introduce extra force demand along the direction of movement whenever the curvature of manipulation is changed by the subject from that estimated by the Kalman filter. In most of the times during welding the subject follows a smoothly curved welding path, which is properly estimated by the Kalman filter; therefore, with appropriate impedance values, he/she hardly feels any force demand along the intended direction. However, when the impedance parameters are not appropriate, the subject has difficulty to stabilize the movement along an intended path. In such

cases, the subject needs to apply a lot of corrective forces to bring the tool to the intended path.

The impedance and variance measurements presented in Table I indicate that the most significant difference between the professional and novice welders occurs with the values in the  $x$  direction. Furthermore, the largest impedance in this direction results in the smallest position variation, compared to the other two directions. Therefore, we choose to use the values of this direction in order to compensate the impedance in all directions perpendicular to the movement.

Based on the impedance measurements, ideally we would like to apply either ‘the average values observed with the professional welders’ or ‘the difference between the average values observed with professional and novice welders’ in the  $x$  direction in Table I. As we will explain in the following, these two sets of parameters did not result in as an effective assistance as a third set where ‘the damping value observed with the professional welders and the difference of stiffness and mass values between the professional and novice welders’ was used. In order to test these three alternatives, we conducted a micro study in the development stage, with airbrush painting as in [38], as a replacement of manual welding. The two tasks resemble each other since they both require large hand impedance for a good performance [1, 38] and they have similarities in the use of the tool and the task performance [18]. In this micro study, a subject did airbrush painting through an S shaped path (Fig. 6(a)), with the non-dominant hand with the four sets of parameters corresponding to:

- i) with no assistance:  $M=0$  (kg),  $D=0$  (Ns/m),  $S=0$  (N/m),
- ii) with the values of professionals:  $M=2.9$ ,  $D=44$ ,  $S=550$ ,
- iii) with the values of difference between the professionals and novices:  $M=0.3$ ,  $D=12$ ,  $S=109$ ,
- iv) with the values of difference between professional and novices except for damping:  $M=0.3$ ,  $D=44$ ,  $S=109$ .

The magnitude of the human force and the assistive forces are plotted in Fig. 6(b, c, e, f) for each set respectively. In Fig. 6(d) the frequency spectrum of the signal  $r$  is plotted for each set. In Fig. 6(a) we observe the fluctuations of the position trajectory with the case where there is no assistance (set i). When we apply the full professional welder values (set ii), the fluctuations do not decrease, and in fact further increase with sharp back and forth movements in some regions. In Fig. 6(c) we see that the stiffness force for this case is dominating and the human force is considerably increased (compare to Fig. 6(b)) to counter the stiffness force. We also observe in Fig. 6(c) that the mass related assistive force is ineffective compared to the others.

When we apply the direct difference of values for professional and novice welders (set iii) we see in Fig. 6(e) that the human effort decreases to its nominal level as in Fig. 6(b), however we still observe fluctuations in the painting trajectory in Fig. 6(a). In order to eliminate these fluctuations we next increase the damping value to the level of average professionals. Please note that increasing the stiffness would cause further fluctuations and increasing the

<sup>1</sup> We report the scheme for the virtual mass related force as it was used in our experiments. However, it is possible to use the mass force also to resist the deviations from the Kalman filter trajectory by simply using the actual acceleration vector (backward derivation of the velocity vector) instead of the Kalman filter acceleration. Such modification resulted in no obvious difference in our application. In cases where larger mass values are to be applied, using the actual acceleration obtained by backward derivation might cause instability due to the noise introduced by backward derivation. One should either use real-time filtering, possibly introducing some delay in acceleration values, or use a second Kalman filter with a larger auto-covariance matrix of process disturbance, just for estimating a smooth acceleration. The impact of such slight differences in the choice of design is not yet studied, therefore we content here by mentioning the potential modifications.

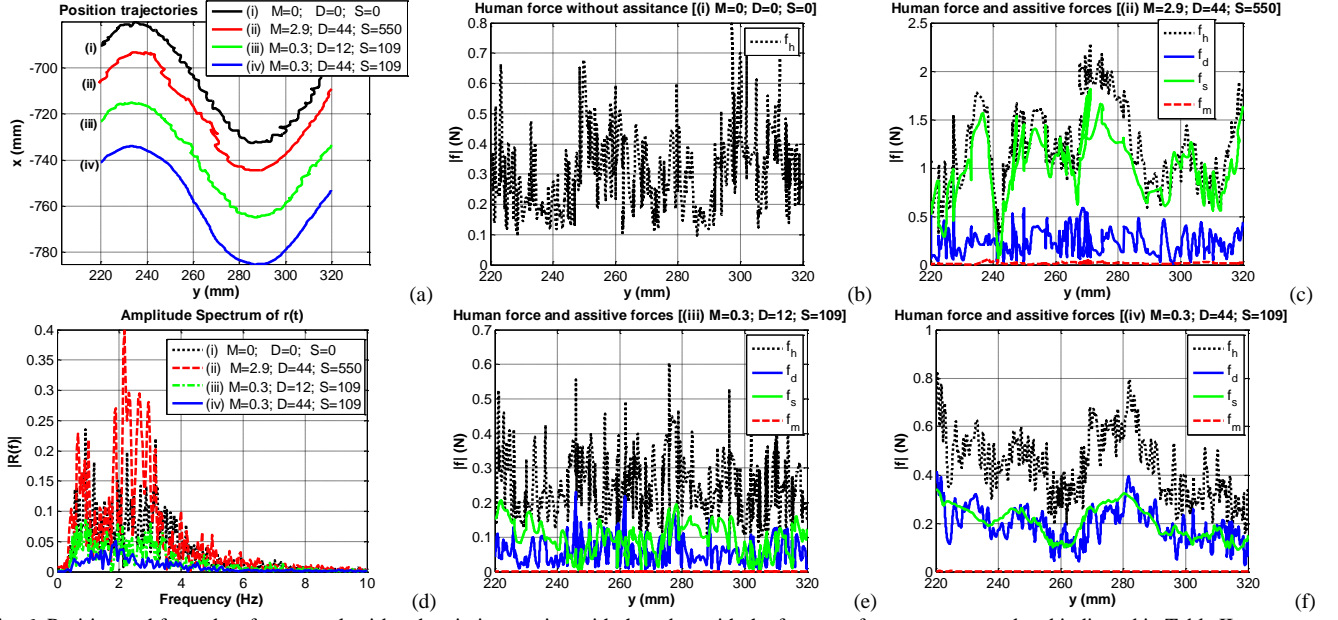


Fig. 6: Position and force data for a sample airbrush painting session with the robot with the four set of parameters tested and indicated in Table II.

mass would not result in an effective assistance as we observed in Fig. 6(c).

By applying the values of *set iv*, we observe in Fig. 6(f) that the human effort is only slightly increased compared to its nominal level in Fig. 6(b) and the fluctuations in the painting path disappear almost totally in Fig. 6(a). In Fig. 6(f) we observe that the damping and stiffness forces with these values are effective for assistance and the mass related force remains ineffective. We also observe in Fig. 6(d) that the power of the signal  $r$  above 0.2 Hz gets minimum values with the *set iv* compared to the others, which indicates an effective suppression of hand vibrations.

In order to further verify the above observations the same subject performed airbrush painting with his dominant hand two times with each of the four set of parameters. The average position variation, human force and elapsed time while painting a specified distance are given in Table II. Considering the position variation and elapsed time, the best performance was achieved with the *set iv*. The force demand with *set iv* is only slightly larger than the cases with no assistance (*set i*) and with application of direct differences of impedance parameters (*set iii*). On the other hand, using the direct values of the professional welders (*set ii*) caused too much position variation and force demand, whereas using the difference of parameters between professional and novice welders (*set iii*), did not result as an effective assistance as the *set iv*, considering both variance and elapsed time.

We also compared the parameter *set iv* with pure damping compensation ( $M=0$ ;  $D=44$ ;  $S=0$ ) as we applied in [35], while 10 subjects did airbrush painting. We observed that 7 of the 10 subjects had less variation with *set iv* compared to pure damping compensation, with an overall mean difference of  $0.20 \pm 0.48 \text{ mm}^2$  for all ten subjects. In Fig. 7, we give the position, force and frequency content figures for

TABLE II  
PERFORMANCE AND EFFORT MEASURES WITH AIRBRUSH PAINTING, USED TO DETERMINE THE SET OF IMPEDANCE PARAMETERS

	Impedance Parameters			Performance/Effort Measures		
	$M$ (kg)	$D$ (Ns/m)	$S$ (N/m)	Variation ( $\mu\text{m}^2$ )	Average Force (N)	Time Elapsed (s)
(i) No Assistance	0.0	0	0	$1.56 \pm 0.56$	$0.25 \pm 0.05$	$19.0 \pm 1.9$
(ii) Full Professional Values	2.9	44	550	$1.86 \pm 0.41$	$1.03 \pm 0.13$	$18.3 \pm 2.6$
(iii) Difference between Pro./Nov.	0.3	12	109	$0.66 \pm 0.01$	$0.23 \pm 0.02$	$19.4 \pm 0.6$
(iv) Difference except damping	<b>0.3</b>	<b>44</b>	<b>109</b>	<b><math>0.56 \pm 0.04</math></b>	<b><math>0.33 \pm 0.03</math></b>	<b><math>16.2 \pm 2.6</math></b>

a sample subject with the *set iv* values and with pure damping compensation. In Fig. 7(a, d) we highlight an instant where the stiffness force is increased with the *set iv* when the hand abruptly deviates from the smooth painting path. In Fig. 7(b, e) we highlight that with the pure damping compensation the damping force increases around the regions where the curvature of the path is changed. We see in Fig. 6(c) that the position signal has less variation in the high frequencies with the parameter *set iv*.

## V. ASSISTANCE REGULATOR: INTEGRAL ASSISTIVE SETUP FOR WELDING

In this section we explain the integration of the robotic assistance by impedance compensation to a general framework of variable impedance control that makes it convenient to use the overall system considering the necessary manipulation before, during, and after an actual welding. During nominal assistance while welding, the block Assistance Regulator in Fig. 2 is not active; therefore the assistive force ( $f_a$ ) is equal to the virtual force ( $f_v$ ). However, in general, the Assistance Regulator block controls the overall assistance policy with respect to the position and speed of the torch and with respect to some



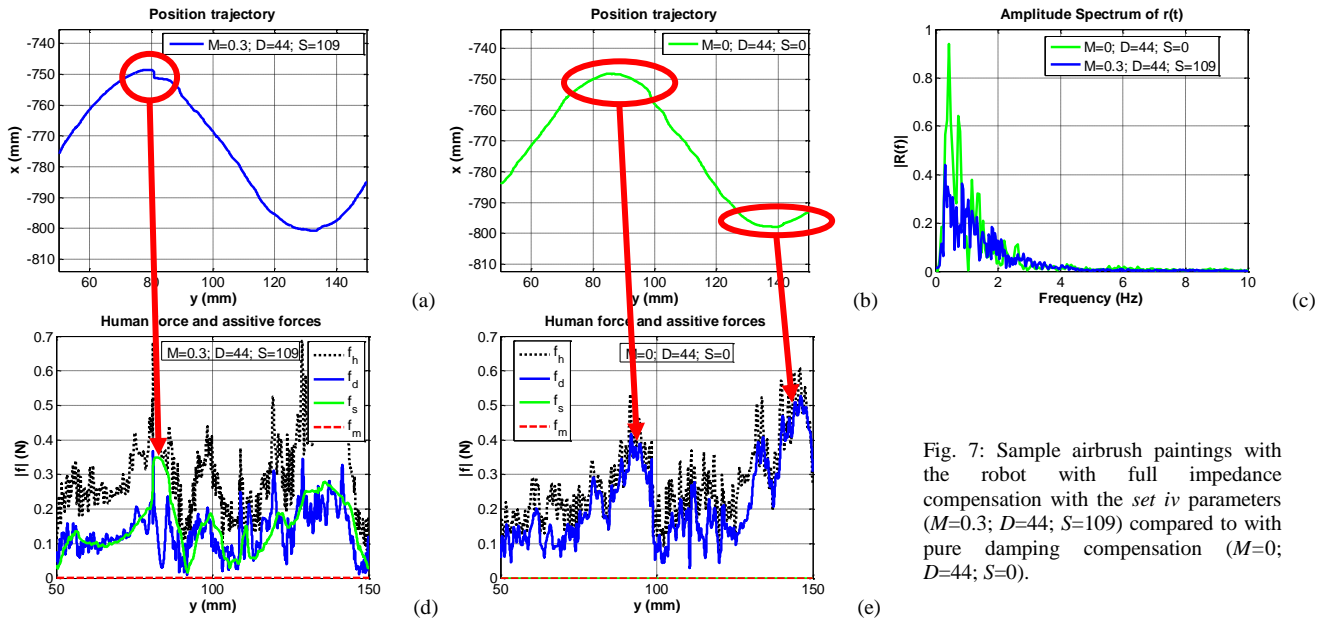


Fig. 7: Sample airbrush paintings with the robot with full impedance compensation with the *set iv* parameters ( $M=0.3$ ;  $D=44$ ;  $S=109$ ) compared to with pure damping compensation ( $M=0$ ;  $D=44$ ;  $S=0$ ).

timing conditions. The function of the Assistance Regulator is to regulate the switching between various control modes in different phases of the usage of the system. Specifically, the following four items are integrated within the block Assistance Regulator.

#### A. Spatial separation between non-welding and welding regions

The type of welding we want to assist in this study is mostly performed on a flat surface on a steel table. Therefore it is convenient to detect the intention of welding or not-welding partially by monitoring the height of the torch from the steel table and to apply different interactive controls accordingly. For example in regions where there is no welding, the assistive scheme can be turned off and the subject can transfer the torch rapidly to any desired position without necessarily following a smooth curve and possibly with jerky motions. Finally the subject can leave the torch at any place in a stable way. In this study, the region higher than 5 cm above the steel table ( $p_z > 5$  cm) is considered to be the non-welding region.

In the welding region ( $p_z \leq 5$  cm), impedance compensation is integrated with variable damping. In this region the subject either welds with assistance or transfers the torch from one point to another. The damping is changed according to the Cartesian speed of the tip of the torch ( $s_c$ ), which is used as an indicator of the intention of the welder for these purposes. In the non-welding region, what is practiced is either to stop the movement of the torch or to translate it towards the welding region. The switching between the two activities is maintained by again variable damping.

#### B. Switching phases within the welding region

In an earlier study we already used and demonstrated the effectiveness of variable damping based on the Cartesian speed of the tip of the welding torch, while welding

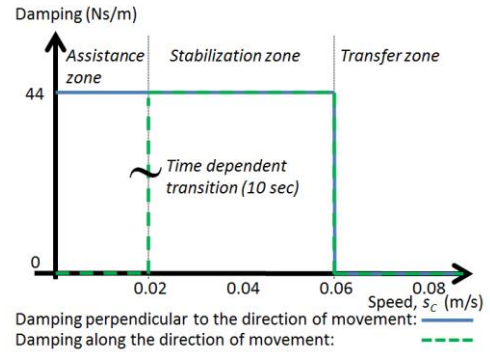


Fig. 8: Damping profile applied within the welding region ( $p_z < 5$  cm).

interactively with a robot [18]. Here we adapt the variable damping approach to transfer between the non-welding (transfer zone) and welding (assistance and transition zones) phases within the welding region. Please refer to Fig. 8 for the explanations of the damping profile in this subsection.

##### 1) Transfer Zone: $0.06 \text{ m/s} < s_c$

When the welder increases the speed above 0.06 m/s the damping in all directions is reduced to zero and an easy translation of the torch is achieved. The value 0.06 m/s is the maximum speed level we observe for professional welders while welding interactively with the robot without assistance. In this zone the subject can stop welding at one point and easily translate the torch to start a new welding at another point, without being restricted by any damping in any direction. The subject might also transit to the non-welding region under this condition.

##### 2) Stabilization Zone: $0.02 \text{ m/s} < s_c \leq 0.06 \text{ m/s}$

This is the stabilization zone where full damping is applied in all directions. In this zone the torch is stable in all directions. The subject can precisely locate the torch at the beginning of the welding line and turn on the welding arc.

##### 3) Assistance Zone: $s_c \leq 0.02 \text{ m/s}$

We activate the impedance compensation when the speed level is below 0.02 m/s. The 0.02 m/s threshold is derived

TABLE III  
MEAN VARIANCE OF POSITION FOR NOVICE AND PROFESSIONAL WELDERS WHILE THEY WELDED WITH THE ROBOT WITHOUT AND WITH ASSISTANCE<sup>†</sup>

	Novice Welders (12 subjects)					Professional Welders (8 subjects)				
	variance (filtered, 0.2 Hz) (mm <sup>2</sup> )		variation (v) (mm <sup>2</sup> )		speed	variance (filtered, 0.2 Hz) (mm <sup>2</sup> )		variation (v) (mm <sup>2</sup> )		speed
	var(x)	var(y)	var(z)	var(x)+var(y)+var(z)	(mm/sec)	var(x)	var(y)	var(z)	var(x)+var(y)+var(z)	(mm/sec)
Without Assistance	0.29 ±0.20	0.60 ±0.36	1.13 ±0.77	2.02 ±1.13	1.61 ±0.51	0.18 ±0.10	0.43 ±0.11	0.78 ±0.37	1.38 ±0.38	0.94 ±0.28
With Assistance	0.14 ±0.07	0.56 ±0.29	0.26 ±0.11	0.96 ±0.41	1.64 ±0.39	0.07 ±0.02	0.32 ±0.23	0.19 ±0.09	0.58 ±0.30	1.50 ±0.38
Decrease (mm <sup>2</sup> )	0.15*	0.04	0.87*	1.06*	Increase	0.11*	0.11	0.58*	0.80*	Increase
Decrease (%)	51	7	77	52	2%	63	25	75	58	60%*
p values (t-test)	0.031	0.731	<0.001	0.002	0.887	<0.001	0.093	<0.001	<0.001	0.005

<sup>†</sup>The groups of which the differences are indicated by the symbol (\*) are found to be significantly different by the three-way ANOVA, with  $p < 0.05$ .

from our previous study of interactive manual welding with robot [18] and it is also a reasonable limit considering the maximum speed values observed with professional welders when they welded conventionally without a robot in the study [16].

Initial melting in the start of welding requires holding the arc at the same point for a few seconds long; because the metal is initially cold. In the start of welding, the impedance compensation includes damping in all directions in order to stabilize the movement. After this it becomes faster to melt the metals along their edges. The damping along the direction of movement is gradually turned off with a time dependent transition.

#### 4) Time dependent Transition to Full Assistance

In the first five seconds after the speed is below 0.02 m/s, the damping is still active in all directions to enable the initial melting in a stable way. After five seconds, the damping along the intended direction (along the velocity vector of the Kalman filter) is gradually reduced to zero in another 5 seconds period. Finally, the original assistance becomes fully active, in total 10 seconds after falling below the speed limit of 0.2 m/s. The subject feels this transition as a stable starting at the beginning and being free to move the torch along the intended direction after some brief time.

### C. Switching phases within the non-welding region

In the non-welding region ( $p_z > 5$  cm) we adapt variable damping to switch between stopping and torch-transfer phases.

#### 1) Relocation zone: $0.06 \text{ m/s} < s_c$

Above 0.06 m/s the damping is reduced to zero. In this way, when the subject wants to relocate the torch in the non-welding region by increasing the speed, the damping is decreased and the subject easily translates the torch.

#### 2) Leaving Zone: $s_c \leq 0.06 \text{ m/s}$

Below 0.06 m/s the damping is fixed to its full value (44 Ns/m) in all directions. This means that when the welder slows down for leaving the torch, the damping is increased and the torch movement is restricted. The robot easily switches into the “stopping” condition at that point.

### D. Stopping of movement when the torch is left aside in the non-welding region

The stopping feature is activated when the two conditions are satisfied simultaneously:

- 1) The torch is within the non-welding region:  $p_z > 5$  cm
- 2) The force applied on the torch drops below 0.1 N for a

period of 3 s

These conditions detect the situation that the welder has left the torch aside and not touched for at least 3 seconds. Once these two conditions are satisfied the robot is stopped by simply commanding zero velocity. In this way, light force signals due to external impacts or noise in the force sensor are ignored and the robot remains stationary. In order to switch from this state, the welder needs to touch the torch again and apply a force larger than 0.1 N, which naturally occurs with any slight human hand movement.

## VI. RESULTS OF PERFORMANCE MEASURE FOR WELDING WITH THE ROBOT WITHOUT AND WITH ASSISTANCE

In this section we evaluate the effectiveness of the assistance by comparing welding with the robot without assistance and with assistance, across professional and novice welders. In Table III we present the mean variance values for the professional and novice welders.

For the data presented in Table III we analyzed the impact of three factors on the variance measures: *mode* of welding (without-assistance/with-assistance), *expertise* (professional/novice), and *direction* (x/y/z/v). We applied log transform to all variance (x, y, z) and variation (v) data in order to achieve a normalized distribution in each of the 16 compared groups, which is a condition to apply ANOVA and t-test. All 16 groups passed either the Lilliefors or the Kolmogorov-Smirnov normality test with a significance level  $p = 0.05$ . We ran a three-way ANOVA test (*anovan()* in Matlab) over the variance data. Finally we performed post hoc analysis using Tukey’s least significant difference procedure (*multcompare()*) to find the groups that significantly differ from each other with respect to any factor. We also applied Student’s t-test (*ttest2()*) to the groups that we report to differ significantly with respect to a factor in the post hoc analysis. In all statistical tests we used  $p = 0.05$  as the threshold (maximum) for statistical significance.

The three-way ANOVA found significant effect due to the factors *mode* [degrees of freedom (d)=1; F statistics (F)=70.63; p value for the F statistics (p)<0.001; effect size ( $\eta^2$ )=0.148], *expertise* (d=1; F=19.76; p<0.001;  $\eta^2$ =0.041), and *direction* (d=3; F=72.85; p<0.001;  $\eta^2$ =0.460). We found significant interaction between the factors *mode* and *direction* (d=3; F=0.33; p=0.002;  $\eta^2$ =0.034), and did not find any significant interaction between the other factors. This result confirms our previous findings that the expertise and direction of welding are significant factors in measure of

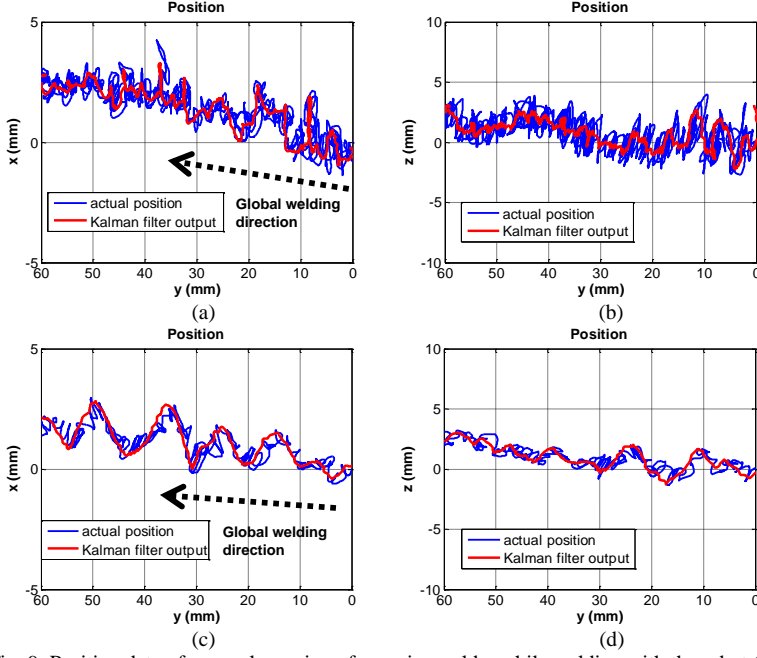


Fig. 9: Position data of a sample session of a novice welder while welding with the robot (a)-(b) without assistance and (c)-(d) with assistance. The global welding direction (along the contacting edges) is through the center of the curves in (a) and (c). The  $z=0$  line in (b) and (d) correspond to the starting point of welding, not to the table level.

variance [1] and further indicate that the robotic assistance makes a significant difference in variance of position.

The post-hoc analysis identified the groups which differed significantly with  $p < 0.05$ . Among those we indicate the difference between the ones that are interesting from comparison point of view with an asterisk in Table III. We observe that there is significant difference in total variance ( $v$ ) of position for both novice and professional welders across welding without and with assistance. We also observe that this is due to the significant difference of variance in  $x$  and  $z$  directions, which are perpendicular to the global welding direction along the contacting edges of the plates. This verifies the effectiveness of the robotic assistance with impedance compensation. We observe that with assistance the variance of the novice welders in these directions are reduced to a level lower than that of the professionals without assistance. In Table III we indicate also the average welding speed of novice and professional welders. The welding speed of the professional welders increased substantially and statistically significantly with robotic assistance. Please note that mastering the welding speed requires experience and knowledge about the best melting of the metal plates assessed by visual inspection. The professional welders have this knowledge and experience but the novice welders do not have. Therefore in this study the criterion of speed applies only to the professional welders.

In Fig. 9 we plot the position data of a sample novice welder for welding with the robot without [Fig. 9(a)(b)] and with [Fig. 9(c)(d)] assistance. We observe in these figures that the chattering of the position signals around the Kalman filter output is largely reduced in the case with assistance.

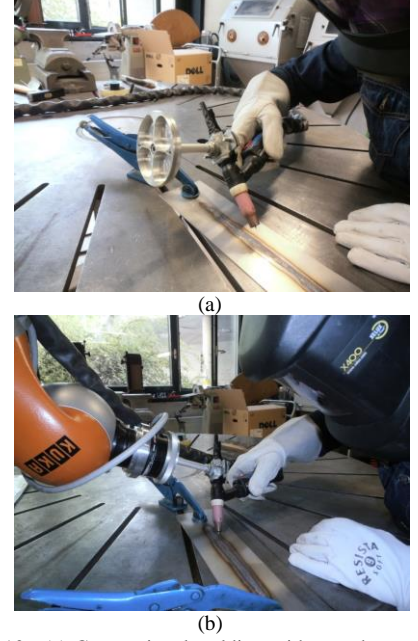


Fig. 10. (a) Conventional welding without robot and (b) welding with robotic assistance.

We observe that in the case without assistance there is a lot of uncontrolled motion with sudden changes of direction, back and forth across the contacting edges of the metal plates [Fig. 9(a)], and up and down in the direction of gravity [Fig. 9(b)]. However, with the assistance, the movements get regular and more controlled: the subject gets back and forth in a controlled way across the edges of the plates to achieve a balanced melting on both sides [Fig. 9(c)]; similarly the subject better controls the height of the torch according to the melting and steadily gets higher due to the bending of the metals in time.

## VII. SUBJECTIVE EVALUATION OF WELDING WITHOUT ROBOT AND WITH ROBOTIC ASSISTANCE: QUESTIONNAIRE

The subjects answered a questionnaire to evaluate the effectiveness of the overall system of robotic assistance [Fig. 10(b)] in comparison to the conventional welding without the robot [Fig. 10(a)]. The questionnaire had three sets of questions. The first set composed of the ten questions of the System Usability Scale (SUS) [50] rated on a five-point Likert scale. In Table IV we report the average SUS scores for the novice and professional welders. (The details of computation of the SUS score can be found in [50].) We observe that the robotic assistance system is perceived more usable by the novice welders than by the professional welders with average SUS scores 81.7 and 60.6, respectively.

In order to analyze the relation between the welding performance and SUS scores, we computed a parameter of skill level ( $s$ ) as in (7), for each individual based on the variance in  $x$  direction, perpendicular to the welding line on the plane of the metal plate. The choice of this parameter



TABLE IV  
SYSTEM USABILITY (SUS) EVALUATION [50]: PHRASES FROM THE  
QUESTIONS AND MEAN SCORES OF THE ANSWERS  
(GRADE 0: "STRONGLY DISAGREE"; GRADE 4: "STRONGLY AGREE")

Questions (Phrases)	Scores (mean $\pm$ std.)	
	Novice (12)	Professional (8)
1 Willing to use frequently	3.0 $\pm$ 0.4	1.6 $\pm$ 1.3
2 Found complex	3.0 $\pm$ 1.0	2.8 $\pm$ 0.9
3 Was easy to use	3.5 $\pm$ 0.7	2.1 $\pm$ 0.8
4 Need for technical support	2.8 $\pm$ 0.9	2.5 $\pm$ 1.2
5 Found well integrated	3.0 $\pm$ 0.7	2.3 $\pm$ 0.7
6 Too much inconsistency	3.1 $\pm$ 0.9	2.5 $\pm$ 0.9
7 Quick to learn	3.9 $\pm$ 0.3	2.6 $\pm$ 0.9
8 Complicated	3.7 $\pm$ 0.5	3.0 $\pm$ 1.1
9 Felt confident	3.2 $\pm$ 0.4	2.3 $\pm$ 0.9
10 A lot of things to be learned	3.5 $\pm$ 0.5	2.6 $\pm$ 0.9
<b>SUS Score</b>	<b>81.7 <math>\pm</math> 6.8</b>	<b>60.6 <math>\pm</math> 14.5</b>

was motivated by our findings in Table I, which showed that the position variation in  $x$  direction was significantly lower than that in  $y$  and  $z$  directions, for both professional and novice welders. No significant difference was found between the other two directions. This indicates that  $x$  direction is the most important to have a good performance in welding. Professional welders demonstrated significantly less variation in  $x$  direction (also in  $z$  direction) compared to the novice welders. Moreover, the hand impedance of professional welders (rate-hardness and damping) was found to be significantly larger than that of the novice welders in  $x$  direction, but not in the other two directions. The parameter of skill level here accounts for the average variation in  $x$  direction with and without assistance for each individual.

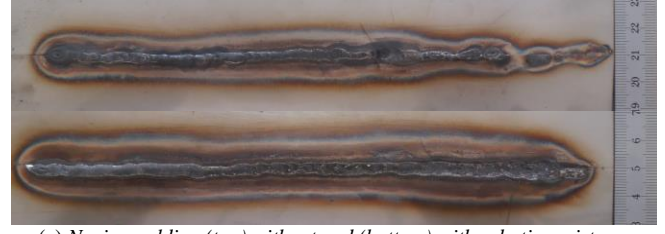
$$S = \frac{1}{\text{var}_{\text{with}}(x) + \text{var}_{\text{without}}(x)} \quad (7)$$

We performed correlation analysis between the parameter of skill level and the SUS scores over the professional and novice subjects and found negative correlation with a factor -0.50 and statistical significance ( $p=0.026$ ). This finding is consistent with the observation in SUS scores that the less skilled subjects find the system more useful.

The second set of questions included the six questions of the NASA Task Load Index (TLX) [51]. Subjects gave their opinion to these questions on a 21 point-scale. The meanings of the extreme points are indicated in Table V for each question. We observe that the average values for the novice (6.9) and professional (8.1) welders are close to each other and both are in the first half of the 1-21 scale. This means that welding with the robotic assistance is not perceived as a heavy load task by the novice and professional welders.

TABLE V  
TASK LOAD (TLX) EVALUATION [51]: PHRASES FROM THE  
QUESTIONS AND MEAN SCORES OF THE ANSWERS  
(GRADED ON A SCALE OF 1-21 POINTS)

Questions (Phrases)	Scores (mean $\pm$ std.) [1, 21]	
	Novice (12)	Professional (8)
1 Mental demand (low/high)	7.5 $\pm$ 4.6	7.8 $\pm$ 4.8
2 Physical demand (low/high)	8.4 $\pm$ 4.5	9.3 $\pm$ 5.7
3 Temporal demand (low/high)	6.5 $\pm$ 4.6	7.5 $\pm$ 2.4
4 Performance (perfect/failure)	6.7 $\pm$ 3.8	9.9 $\pm$ 6.3
5 Effort (little/much)	9.2 $\pm$ 5.6	7.8 $\pm$ 5.2
6 Frustration (low/high)	3.0 $\pm$ 2.0	6.5 $\pm$ 4.7
<b>TLX Score</b>	<b>6.9 <math>\pm</math> 4.6</b>	<b>8.1 <math>\pm</math> 4.9</b>



(a) Novice welding (top) without and (bottom) with robotic assistance



(b) Professional welding (top) without and (bottom) with assistance

Fig. 11. Sample welding results of a novice and a professional welder without the robot and with robotic assistance.

The last set of questions was custom prepared to directly compare the welding without the robot and welding with robotic assistance. It included six closed-form (Table VI) and four open-ended questions. We observe in Table IV that all the novice and most of the professional welders found welding with robotic assistance easier and more successful than welding without the robot. The novice welders more clearly indicated that the robot was assisting (with a score 5.6), the professional welders doubted more about that (with a score 11.6). In Fig. 11 we present sample welding results from a novice and professional subject without the robot and with robotic assistance. We observe that there is a significant improvement in the regularity of the weld of the novice subject with the robotic assistance. For the professional welder we do not observe a significant quality difference: both the weld without the robot and the weld with the robotic assistance are regular and in good shape.

We also asked questions to test whether the schemes applied for leaving the torch in air while not welding and for starting the arc before welding were functional. Both novice and professional welders indicated that both actions were rather easy (with scores in the first half of the 1-21 scale).

Here we report two of the four open-ended questions with sample answers given by novice and professional welders.

- 1) If you think the robot was assisting, in what way it was easier with the robot?
- 2) If you think the robot was assisting the welding, what

TABLE VI  
CUSTOM EVALUATION FOR COMPARISON OF WELDING WITH ROBOTIC ASSISTANCE AND  
WELDING WITHOUT ROBOT: PHRASES FROM THE QUESTIONS AND MEAN SCORES

Questions	Novices (12)		Professionals (8)	
	With assistance	Without robot	With assistance	Without robot
1 Easiness (voting)	12	0	5.5	2.5
2 Success (voting)	12	0	5.5	2.5
<i>mean score <math>\pm</math> std. (over 21)</i>				
3 Robot was assisting? yes (1), no (21)	5.6 $\pm$ 2.1		11.6 $\pm$ 5.3	
4 Did you have any difficulty? yes (1), no (21)	15.3 $\pm$ 4.2		13.0 $\pm$ 4.5	
5 Leaving the torch was easy? yes (1), no (21)	3.9 $\pm$ 3.8		8.9 $\pm$ 6.9	
6 Starting the arc was easy? yes (1), no (21)	4.3 $\pm$ 3.0		6.5 $\pm$ 7.1	



*do you think the robot was doing?*

Novice Welders:

*"It felt like the robot was helping to make a straight welding line (preventing zigzags)."*

*"Feeling my moves when started and instantly helping me to do them."*

*"It is easier to keep the same distance between the welding machine and the metal."*

Professional Welders:

*"The robot made a good assistance in [perpendicular] direction."*

*"It's too easy to stabilize my hand with the robot."*

Considering the first question almost all novice welders emphasized that they felt the robot assisting. Some of the professional welders indicated that they felt the robot assisting, and some others were either indifferent or critical, that they said the robot was more disturbing than assisting. Considering the second question, almost all novice and professional welders identified that the robot was suppressing the movements in the directions perpendicular to the welding direction and allowed easy movement along the welding direction. The statements clearly showed that the assistance by the robot was perceived as it was intended (suppression of movements in the directions perpendicular to the hand movement) and appreciated by all novice and most professional subjects.

## VIII. CONCLUSION

In this study we developed a robotic assistance scheme which allows compensating the hand impedance with the three parameters of stiffness, damping and mass and we applied it to manual welding. The scheme and the impedance parameters were inspired from our hand impedance measurements while welding, presented in a recent study [1]. The assistive scheme makes use of a smooth Kalman filter in order to generate an estimate of the intended direction of movement for welding in real-time. The virtual dynamics of the robot is controlled to provide compensatory impedance perpendicular to the estimated direction. In this way the hand tremor perpendicular to the welding direction is effectively suppressed.

We tested the scheme with both professional and novice welders and assessed the effectiveness both quantitatively with variance measures and qualitatively with a user questionnaire. The results demonstrate that the robotic assistance is effective to improve the performance of all novice and most professional welders.

The Kalman filter used in this scheme estimates the intended path correctly only when it is a smooth curve; it will not estimate correctly if the subject makes intentional sharp turns and this will create large forces resisting the turn. With the kind of welding we study (TIG welding of pieces on steel table), sharp turns during a welding session is not a custom practice; because it is difficult to maintain position precision when the hand makes such turns. Professional welders rather divide the overall path into almost linear

segments and weld each segment separately using a hand-body configuration to provide maximum impedance in the perpendicular direction to the welding segment. Therefore, our assistive scheme is adaptive to accommodate the smooth curvatures of welding lines and the smooth weaving movements across the welding line as experienced in practice. We should mention here that, our approach is also promising for advanced manual welding, like tube welding, where the welding line is smoothly changing on the surface of the tube, but it is difficult to maintain proper hand impedance because the surface is not flat. For other applications than manual welding, where there are sharp turns, it might be necessary to estimate the turning points and artificially decrease the level of assistance in order to avoid excessive force demand.

In this study we used the impedance values observed in our previous study: the average damping value with professional welders, and the difference of mass and stiffness values between professional and novice welders. Although with airbrush painting experiments we compared this choice with alternatives – two alternative sets of values and a pure damping compensation – which could be inspired from the same impedance measures, we did not tune the values in order to improve the effectiveness of the robotic assistance. This was because, at this stage, we wanted to see the impact with the direct application of the measured values. The effectiveness can be improved by tuning the applied impedance values, especially by slightly increasing the damping value and by introducing slight damping also along the estimated direction of movement. For applications to other tasks than welding, the impedance compensation can be taken as a basis scheme and the best impedance values can be tuned or learned by experiments.

The assistive scheme we present applies impedance compensation with constant values, regardless of the variability of the human hand impedance with and within subjects. Ideally we would like to estimate the hand impedance in real-time and compensate it depending on the estimated level to achieve optimal performance. At this stage we are far from a precise enough real-time hand impedance estimation; therefore, the current scheme does not necessarily provide optimum assistance for every individual. Future work will be devoted to developing a precise enough real-time hand impedance estimation to achieve near-optimal performance for each individual.

We believe that the scheme of robotic assistance by impedance compensation can be applied to various manipulation tasks where the goal is to follow a curve using a tool at hand and where it is desirable to suppress the impact of hand tremor, typical in welding, painting, polishing, and writing.

## IX. ACKNOWLEDGEMENT

The authors would like to thank to the anonymous novice and professional welders that took part in this study. Special thanks go to the professional welder Nicolas Jaunin who also

prepared the metal plates used in this study.

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